INTRODUCTION

The possibility of elastic properties measurements on a microscopic scale for the materials and structures nondestructively is one of the advantages of the scanning acoustic microscopy. This type of investigation is based mainly on the $V(\zeta)$ method. In this method, the output radio signal of an acoustic transducer is measured as a function of the sample displacement along the lens axis.

The shape of the $V(\zeta)$ curves depend on the acoustical properties of the investigated surface. It is possible to measure the velocity and attenuation of surface acoustic wave (SAW) by the analysis of the period and shape of the specific dips in the negative $\zeta$ region of $V(\zeta)$ [1]. This technique utilizes only the magnitude of $V(\zeta)$ data produced by the rectification of the reflected tone burst signals.

At the same time complex reflectance $R(\theta)$ of the specimen interface, as a function of the angle $\theta$ between the direction of an incidence plane wave and the normal to the interface surface, contains more information about acoustical parameters. As was shown [2] reflectance function $R(\theta)$ can be obtained by inverse Fourier transformation of the complex $V(\zeta)$. To realize this powerful technique, it is necessary to measure both amplitude and phase of the $V(\zeta)$ function. Generally, it is not trivial to measure the phase of high-frequency tone burst signals with accuracy, so a special complicated precision phase measurement system was designed [3].

Another approach to obtain both amplitude and phase information, is based on the use of a Continuous Wave Reflection Scanning Acoustic Microscope [4,5]. In this device, the Continuous Wave $V(\zeta)$ curve is defined as
electrical reflection coefficient of the transducer and is measured as a function of the sample position. The resulting curve is a mixture of standing waves in the water between the lens and the specimen, and therefore, some of the difficulties in the estimation of the quantitative parameters have arisen.

In this paper we propose a material characterization method based on inversion of the Doppler continuous wave microscope signal. In this method, the relative movement of a sample and acoustic lens is made with constant velocity along an acoustic axis. Because of the Doppler effect, the wave reflected from a moving surface experiences a frequency shift in relation to the probe signal. The occurrence of this shift in frequency, provides an opportunity to receive a reflected signal by processing in frequency, instead of in time domain.

THEORY

The Doppler frequency for the plane wave, that is incident to the moving interface, is equal to the value [6]:

$$\omega_d = 2k_z v_0$$

Here, $v_0$ is the velocity of movement, $k_z = k_0 \cos(\theta)$ is z component of the wave number $k_0$ for the wave in immersion media.

Each component of an angular spectrum of a reflected wave, has a certain value for the Doppler shift. Therefore, by spectral analysis of the output signal it appears to be possible to estimate reflectance function $R(\theta)$. The unitary reflected signal occupies a band of frequencies, which are determined by the maximum aperture angle $\theta_m$ of the acoustic lens: $(2k_0v_0 \cos(\theta_m), 2k_0v_0)$. The signal, reflected from the moving surface twice, receives accordingly, a double frequency shift and occupies frequency band $(4k_0v_0 \cos(\theta_m), 4k_0v_0)$, and so on.

If $\cos(\theta_m) > 0.5$, which is almost always fair, the spectra of these signals are not overlapped, and by the filtering of a unitary reflected signal, the problem of standing waves in the liquid can be solved.

Suppose an acoustical field, represented by $h_1(x,y,t)$ is created at the focal plane of the lens. The spectrum of this field in spatial and temporal domain can be stated as Fourier transform:

$$H_1(k_x,k_y,w) = \mathcal{F}[h_1(x,y)]$$

(2)

This wave is propagated to the sample plane that is separated from the focal plane by the distance $z$, reflected from sample-liquid interface and returned to the focal plane. The spectrum of this field can be expressed as:

$$U(k_x,k_y,w) = H_1(k_x,k_y,w) \cdot R(k_x,k_y,w) \cdot \exp(-2ik_zz).$$

(3)

Accordingly the field $u(x,y,t)$ at this plane, is represented by inverse Fourier transform. This wave is received by an acoustic system with a response function $h_2(x,y,t)$. The output signal of the receiving system as a function of its'
position \((x,y)\) at the focal plane of the first lens, object displacement \(z\) and time \(t\) can be found by convolution:

\[
V(x, y, z, t) = u(x, y, t) \star h_z(x, y, t).
\]

(4)

By applying convolution theorem and substituting in (3), (4) can be written in the form:

\[
V(x, y, z, t) = \mathcal{F}^{-1}\left[H_1 H_2 R(k_x, k_y, w) \exp(-2ik_z z)\right],
\]

(5)

where \(H_2(k_x, k_y, w)\) is the transfer function of the receiving system defined as similar to (2).

The receiving and transmitting lens is the same lens in a considered measuring system configuration. Movement of the receiving lens, relative to transmitted one, is impossible and it is therefore necessary to make \(x=y=0\). Expression (5) for homogeneous specimens can be stated in the polar coordinate system, neglecting the constant factor:

\[
V(z, t) = \int \int H_0(k_z, w) R(k_z, w) \exp\left(-i(2k_z z + wt)\right) dk_z dw.
\]

(6)

Here, general measurable transfer function of the system is equaled

\[
H_0(k_z, w) = \int_0^{2\pi} H_1(k_z, \varphi, w) H_2(k_z, \varphi, w) k_z d\varphi.
\]

(7)

For the continuous wave microscope, with an interrogating signal of frequency \(\omega_0\) this function can be represented as

\[
H_0(k_z, w) = H_0(k_z, w_0) \cdot \delta(w - w_0),
\]

(8)

where \(\delta()\) – delta function. Suppose also the lens to object movement is defined by \(z=\nu_0 t\). For this case by changing variable (1) equation (6) becomes

\[
V(t) = \frac{1}{2\nu_0} \int_{-\infty}^{\infty} H_0 \left(\frac{w_0}{2\nu_0}, w_0\right) R \left(\frac{w_0}{2\nu_0}, w_0\right) \exp\left(-i(w_0 + \nu_0 t)\right) dw_0.
\]

(9)

and the spectrum of this output signal is equal, neglecting constant factor

\[
S(w - w_0) = H_0 \left(\frac{w_0}{2\nu_0}, w_0\right) R \left(\frac{w_0}{2\nu_0}, w_0\right).
\]

(10)

Thus, the spectrum of Doppler signal is determined by the product of reflectance function and general pupil function of acoustic system. This inversion algorithm is equivalent to the algorithm, obtained in work [2] for an pulse echo microscope. In essence both of these methods are based on the fact, that the reflection from a relocatable surface with various angular spectrum
components receives different phase or frequency shifts. The value of this shift depends on the propagation angle, that allows a selection of responses in the output superposition signal.

MEASUREMENT SYSTEM

The considered theoretical principles were applied to the design of the continuous wave Doppler microscope. Fig. 1 shows the block diagram of the device used in the experiments, carried out at the frequency of 300 MHz.

The excitation of an acoustic lens is made by the continuous wave low-noise generator. The sum of the signal, reflected from the sample surface, and the powerful electrical breakthrough is processed by the mixer. The low-frequency output signal of the mixer contains Doppler contributions that correspond to several reflections. The unitary reflected signal is selected by the analog bandpass filter, and then is converted into digital form for the computer processing.

The acoustic lens is located on a mobile frame, that is supported by flat springs and driven by a voice coil system. Laser interferometer was used for scanning coordinate measurements, with the necessary accuracy. The laser beam of the measuring interferometer channel was reflected from a mirror, that was fixed on a mobile frame. The output signal of interferometer, after necessary electronic processing, was used as a trigger signal for analog to digital conversion.

Figure 1. The block diagram of the Doppler continuous wave scanning acoustic microscope.
At the stage of digital processing the spectrum of a signal was displaced by multiplication of a complex continuous wave and filtering one of the side bands. Finally the signal is exposed to apodization, decimation and FFT.

EXPERIMENTAL RESULTS

With the help of this designed microscope the experimental investigation of the layered structure copper – alumina (97% Al₂O₃) was carried out. The thickness of the copper film was varied from 1.7 to 4.1 µm. Fig. 2 shows the measured amplitude |V(z)| and phase arg[V(z)] of the signal for the different layer thicknesses. It is clearly visible that the V(z) signal is not periodic and it is impossible to use the well-known method, based on the periodicity of the signal amplitude.

Figure 2. Experimental V(z) and S(m) curves, m=k₂/k₀, for Cu/Al₂O₃-ceramics structure. The film thickness: a) h = 1.7 µm, b) h = 3.3 µm.
The calculated spectrum amplitude $|S(m)|$ and phase $\arg[S(m)]$, where $m=k/k_0$, also is shown in fig. 2. The spectrum of the signal is determined by the product of the reflectance function and general pupil function of the acoustic system. Measurements of the generalized pupil function of an acoustic lens element were carried out by the investigation of lead, because the reflectance function for lead is basically constant for incident angles $\theta < \theta_m$. Experimental pupil function has a phase that is equal to approximately zero. Therefore, the amplitude of a measured spectrum (fig. 2) is determined by the amplitude of the pupil function, and the phase is determined by the phase of the reflectance function.

The phase of the reflectance function of the structure with the copper layer thickness $h=1.7 \, \mu m$ undergoes rapid $2\pi$ change in the vicinity of SAW critical angles (fig. 2(a)). It is clearly visible that there is a multimode SAW excitation for this sample at a frequency of 300 MHz. The velocities of these two waves modes $R$ and $S$ depend strongly on the film thickness (fig. 2(b)).

The calculated spectra are smooth because of the limitation of the data window. The influence of this smoothing is appreciably stronger for SAW with low attenuation, due to rapid phase change at the critical angle. Such distortions can be consistent with the changes of the phase behaviour (fig. 2(b)) and with the occurrence of sharp dips in the module (fig. 2(a)). The similar typical distortions were investigated in work [2].

The measured dispersion relationships of SAW are plotted on fig. 3. Experimental data were compared with the results of numerical simulation, based on theoretical approach developed in [7]. Calculations were done with the values for alumina: density $\rho=3.97 \, kg/m^3$, longitudinal wave velocity $v_l = 10822 \, m/s$, shear wave velocity $v_s = 6163 \, m/s$; and for copper: $\rho=8.97 \, kg/m^3$.

Figure 3. Measured (dots) and calculated dispersion relationships for SAW exited in Cu/ Al$_2$O$_3$ layered structure.
\( v_l = 4760 \text{ m/s}, \quad v_s = 2330 \text{ m/s} \). In this case the perturbed Rayleigh wave exists for all layer thicknesses and is the lowest-order mode. Another mode corresponds to the Sezawa wave. Comparison between experimental and theoretical dispersion dependences demonstrates satisfactory agreement.

CONCLUSION

For quantitative evaluation of elastic properties, a Doppler continuous wave scanning acoustic microscope has been developed. The Doppler frequency shift of reflected wave is created by moving the lens toward the sample surface with constant velocity. Theoretically, it was estimated that the spectrum of the Doppler signal is determined by the product of the reflectance function and the general pupil function of the acoustic system.

The design of the microscope with an operating frequency of 300 MHz was tested on the investigations of the layered ceramic structure Cu/Al₂O₃. Excitation of the Rayleigh and Sezawa modes of SAW was observed. The dispersion relationships of these modes was investigated experimentally and theoretically.

REFERENCES